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VOLATILE CHALCOPHILE, SIDEROPHILE AND LITHOPHILE TRACE ELEMENTS IN LUNAR METEORITE YAMATO-82192

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Abstract: Neutron activation analyses of Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn in whole-rock, melted and unmelted regolith samples of Yamato-82192 reveals a lunar highlands origin plus meteorite admixture, 2.4± 0.8% Cl-equivalent for micrometeorites and ancient impact component. A small but real amount of mobile element loss occurred during the shock-melting episode that formed Y-82192. Differences in trace element and other trends indicate pronounced differences in the thermal histories of the parent regoliths of Allan Hills A81005 and Y-791197 and -82192 so that each must have been produced by a separate impact on the Moon.

1. Introduction

The discovery and identification of Allan Hills A81005 (31.4 g) and Yamato-791197 (52.4 g) as lunar meteorites answered the question of whether Earth had, by a natural process, ever sampled its nearest neighbor (MARVIN, 1983; YANAI and KOJIMA, 1985). These discoveries also removed a major impediment to the notion that at least some of the SNC meteorites, *i.e.* the shergottites, derive from Mars (WOOD and ASHWAL, 1981; *cf.* FUKUOKA *et al.*, 1986a). Previous consortium studies revealed that, while exhibiting substantial differences in *e.g.* thermal histories (VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986), ALHA81005 and Y-791197 were sufficiently similar to indicate derivation from the same general lunar region (LINDSTROM *et al.*, 1986; TAKEDA *et al.*, 1986). Whether these samples were launched Earthward by one or two large impacts on the Moon was, however, unsettled.

Study of two additional lunar meteorites (YANAI and KOJIMA, 1985), Y-82192 (36.7 g) and Y-82193 (27.0 g), could shed light on this question. The discovery of these close together on the ice sheet and their generally similar unique appearance, even on very superficial examination, suggested pairing. Detailed studies verify this (BISCHOFF *et al.*, 1986; FUKUOKA *et al.*, 1986b). Like the other lunar meteorites, Y-82192 and -82193 (hereafter called Y-82192/3 unless a specific specimen is referred to) are regolith breccias but, unlike them, Y-82192/3 on visual inspection consists mainly of impact melt with but a small portion having the unmelted appearance of ALHA81005 and Y-791197.

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Contents of volatile/mobile (Ga, Se, Te, Bi, Ag, In, Tl, Zn, Cd) trace elements and less volatile siderophiles (Co, Au, Sb) and lithophiles (Rb, Cs, U) provide sensitive markers of chemical and physical fractionations. It was thought worthwhile therefore to determine these elements in Y-82192/3 and compare these with concentrations in the two lunar meteorites studied previously (VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986) to deduce similarities and/or differences in genetic processes. As part of our consortium study, we wished to examine whether mobile element loss occurred during the shock-melting episode evident in Y-82192/3. Finally, we wished to compare the likelihood for single and multiple ejection events for lunar meteorites.

2. Experimental

Our samples of Y-82192 included 28 and 42 mg aliquots of unmelted and shock-melted regolith, respectively, co-existing in a single chip (,52C) with a very sharp lithologic boundary. We separated these easily be chipping and denoted them as ,52C1 and ,52C2, respectively. We also analyzed a 10 mg separated white clast (,83C) that appeared unmelted. Other investigators allocated immediately adjacent samples are: WARREN and KALLEMEYN (1986)-two clasts (,52A and ,83B); FUKUOKA *et al.* (1986b)–matrix (,52B-2 and ,83B-2) and clasts (,52B-1 and ,83B-1).

Other than an increased irradiation time (14 days) because of the small sizes of the individual samples and the low trace element contents expected, techniques used for analysis of Y-82192 were those described by KACZARAL *et al.* (1986). Chemical yields

Table 1. Trace element data for Yamato-82192/3 lunar meteorite.

	Y-82192 (this work)			Other data**
Element*	,52C1	,52C2	,83C	
Siderophile				
Co (ppm)	14.8	12.6	8.4	16.7 (a); 19.9 (b); 17 (c); 11 (d)
Au	12.1	7.1	1.2	(1.4) (a); 1.1 (b); 1.1 (c); 0.7 (d)
Sb	4.2	2.2	2.8	<100 (b)
Ga (ppm)	2.86	3.10	3.18	2.9 (a); 3.78 (b)
Mobile				
Se	338	332	504	<200 (b)
Te	22.3	14.1	≤2.8	
Bi	3.9	2.4	4.5	
In	2.6±0.2	2.0±0.1	0.38±0.21	
Ag	3.7	3.7	2.7±0.3	
Zn (ppm)	4.63	3.03	1.30	4.6 (a); 30 (b)
Tl	3.0	2.5	3.2	
Cd	20.2	21.4	4.6±0.8	
Lithophile				
Rb	230	217	61.8	<3000 (b)
Cs	19.9	15.1	4.8	<100 (b)
U	50.6	47.6	7.0	50 (b); 39 (c); 35 (d)

* Values quoted are in ppb unless otherwise noted.

** Data are whole-rock analyses of Y-82192 unless otherwise noted. References: (a) WARREN and KALLEMEYN (1986); (b) BISCHOFF *et al.* (1986); (c) FUKUOKA *et al.* (1986b)—average of 5 matrix samples of Y-82192/3; (d) FUKUOKA *et al.* (1986b)—average of 3 clasts from Y-82192/3.

exceeded 50% for all monitors and most samples. Three elements had lower average yields–Cs (40%), Ga and In (30%) –as did Ag in ,52C2 and ,83C which averaged 25%. Radiochemical purity was quite satisfactory in all cases.

3. Results

Data for unmelted and melted regolith portions of ,52C are quite similar (Table 1): relative standard deviations range from 0.4–45%, averaging 17%. These results for texturally quite different Y-82192 aliquots are only slightly less precise than those for duplicate analyses of ALHA81005 (VERKOUTEREN *et al.*, 1983): relative standard deviations for this range from 2–21%, averaging 11%. Hence, these two lunar meteorites, unlike Y-791197 (KACZARAL *et al.*, 1986), are chemically homogeneous on the cg scale. Not surprisingly, trace element contents in the clast differ from those in the regolith sample: 8 elements (Au, Cd, Cs, In, Rb, Te, U and Zn) in ,83C are factors of 4–10× (average 6×) lower than in ,52C (Table 1).

For only 5 elements do other data exist with which our results can be compared: upper limits are reported by others for 4 other elements (Table 1). All Co and Ga data agree, as do whole-rock U results. Our U datum and that of FUKUOKA *et al.* (1986b), 11 ppb, for clast ,83 agree reasonably well. Their U data for 2 other clasts are considerably higher. The Zn datum of WARREN and KALLEMEYN (1986) is in excellent agreement with our whole-rock results but that of BISCHOFF *et al.* (1986) is 6× higher for some unknown reason. Our biggest concern is with Au since our whole-rock results are 10× higher than those of BISCHOFF *et al.* (1986) and FUKUOKA *et al.* (1986b). (WARREN and KALLEMEYN (1986) considered their datum suspect but it resembles results by others.) The discrepancy cannot reflect systematic problems since our Au value for clast ,83C is similar to clast data of FUKUOKA *et al.* (1986b). Since Au (and Ir, Re, Ni and Ge) is known as an indicator of ancient meteorite impacts on the Moon (*e.g.* GANAPATHY *et al.*, 1973), we ascribe the Au excess in Y-82192,52C to that source.

4. Discussion

To facilitate discussion, we depict our individual data for Y-82192 (Table 1) in Fig. 1 together with means and ranges for ALHA81005 (VERKOUTEREN *et al.*, 1983) and Y-791197 (KACZARAL *et al.*, 1986), All concentrations are normalized to those in C1 chondrites.

The overall similarity between whole-rock data for Y-82192,52C1 and C2 is striking in view of the very different textures of these samples. Hence, to a first approximation, the shock event that produced ,52C2 did not fractionate mobile elements substantially. However, the data hint at minor loss of some of these: where there are differences (Au, Bi, Co, Cs, In, Sb, Te, Tl, Zn) contents in ,52C2 fall below those in unmelted ,52C1 (Table 1; Fig. 1).

Trace element trends in Y-82192,52C are similar to those in ALHA81005 and suggest a lunar highlands origin. Lithophiles, particularly Rb and Cs, are especially similar: U is about 2× lower in Y-82192. The unusually high Ga contents of all 3

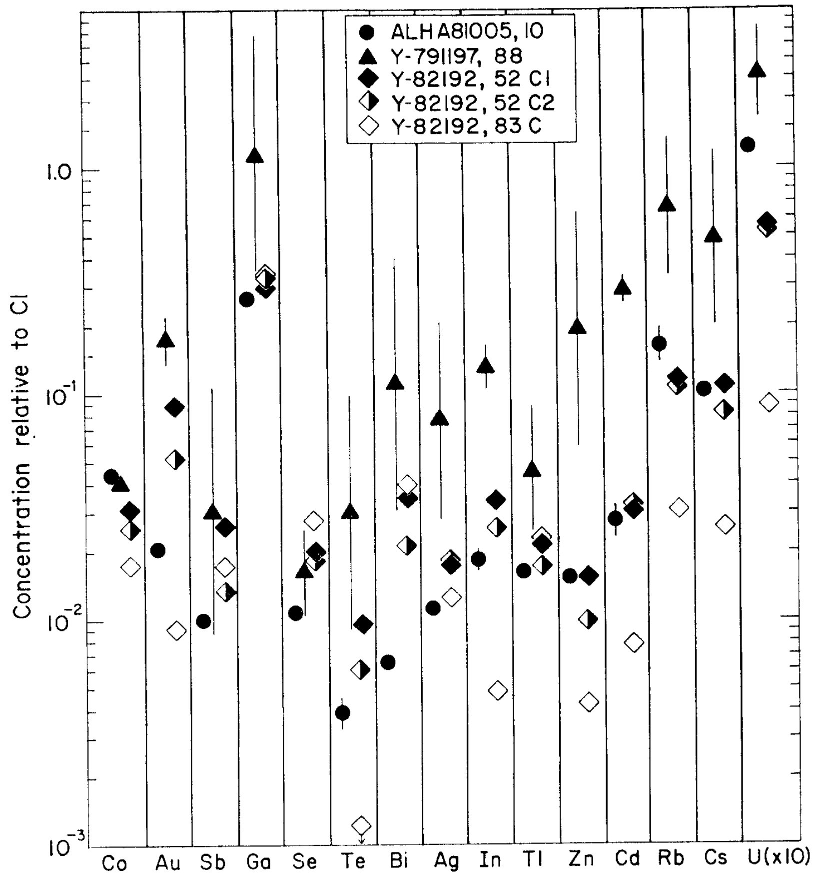

Fig. 1. Trace element concentrations in unmelted and melted whole-rock samples (Y-82192,52C1 and C2, respectively), a white clast (Y-82192,83C) and mean values for ALHA81005 (arithmetic, VERKOUTEREN et al., 1983) and Y-791197 (geometric, KACZARAL et al., 1986). Vertical lines indicate ranges for duplicate analyses: where none is seen, the symbol size exceeds the range. All data are normalized to concentrations in C1 chondrites. Data for Y-791197 are highest because this sample contains condensed lunar volcanic exhalation. Most mobile chalcophile and siderophile elements indicate micrometeorite admixture, 2.4±0.8% and 1.3±0.5% C1-equivalent, in Y-82192 and ALHA-81005, respectively. Lithophiles indicate lunar highland origin. The systematic location of data for Y-82192,52C2 at or below those for ,52C1 implies small but real mobile element loss from the former during the shock-melting event that produced it. Each specimen apparently derives from regolithic materials of different thermal history, hence, was launched Earthward in a separate event (see text).

lunar meteorites and their generally similar concentrations in ALHA81005 and Y-82192 suggests that this normally siderophilic element is largely lithophilic in these lunar meteorites (Fig. 1). Its high variability in Y-791197 is not unique, suggesting lunar volcanic, perhaps fumarolic, enrichment in this meteorite (KACZARAL *et al.*, 1986). Gallium and Zn enrichments in Y-791197 have been confirmed by BISCHOFF and PALME (1986) who suggest that Apollo orange soil 74220 may constitute a better volatile-rich lunar match for Y-791197 than "Rusty Rock", 66095 (KACZARAL *et al.*, 1986). Whatever the case, our observation (KACZARAL *et al.*, 1986) that Y-791197 is one of the most volatile-rich samples obtained from the Moon is confirmed: whether this indicates a more volatile-rich lunar interior than hitherto thought (BISCHOFF and

PALME, 1986) must be established. It is not surprising then that, relative to mean values in Y-791197, 12 of 15 elements (Co, Sb and Se excepted) in Y-82192,52C have contents $\geq 2\times$ lower (Fig. 1).

Relative to ALHA81005, Au and, to a lesser extent, Sb contents in Y-82192 are higher: Co, the only other siderophile, is lower. Whole-rock data for all remaining volatile/mobile elements (Ag, Bi, Cd, In, Se, Te, Tl, Zn), like those for Co and Sb, indicate uniform levels of meteoritic admixture, $2.4\pm0.8\%$ Cl-equivalent (Fig. 1), an unusually high value for lunar regolith samples. The pattern resembles that in ALHA-81005 but the meteorite admixture level in that sample is lower, $1.3\pm0.5\%$ Cl-equivalent (VERKOUTEREN *et al.*, 1983).

While, overall, meteorite admixture occurred in both ALHA81005 and Y-82192, this seems have happened in somewhat different fashion in the two. Solar gases are present in ALHA81005 (and Y-791197) in amounts similar to those in typical lunar regolith samples while they are essentially absent in Y-82192 (TAKAOKA, 1986; WEBER *et al.*, 1986). Since volatile/mobile trace elements contents in ALHA81005 are about those of typical lunar regolithic samples (VERKOUTEREN *et al.*, 1983) it seems reasonable that they and solar gases were implanted into fine-grained soil on the regolith surface (*cf.* NISHIIZUMI *et al.*, 1986).

In Y-82192/3, the absence of irradiation effects indicative of $<4\pi$ exposure to cosmic rays, *i.e.* as other than a small object after ejection from the Moon (NISHIIZUMI *et al.*, 1986), coupled with the absence of solar wind gases imply deep burial and no regolith gardening (TAKAOKA, 1986; WEBER *et al.*, 1986). Meteorite admixture measured by volatile/mobile elements (Fig. 1) must have occurred unusually quickly, otherwise solar gases would also have been implanted: this is even more striking since the admixture level in Y-82192 is so high. It is interesting that Pb in Y-82192 is entirely of meteoritic (or terrestrial) origin while that in ALHA81005 and Y-791197 has the unique lunar Pb isotopic signature (NAKAMURA *et al.*, 1986). The uniformity of volatile/mobile element enrichment in Y-82192 implies fine-grained meteorite addition into regolith soil, *i.e.* prior to its compaction into the Y-82192/3 breccia. Hence, micrometeorite addition in this case must have occurred earlier rather than later in the Moon's history.

Differences in trace element trends reported here and earlier (VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986) demonstrate that no two lunar meteorites were ever part of the same rock. Indeed, to the extent that each breccia is representative of the regolithic material from which it derives, the subtle but real trace element differences argue that the parental regoliths had different thermal histories. Hence, the weight of trace element evidence lies on the side of a separate origin and impact for each of the 3 distinct lunar meteorites, ALHA81005, Y-791197 and -82192/3. In fact, no matter what the measurement (noble gas content, irradiation history, etc.) the same conclusion emerges. Antarctica thus provides us with a record of multiple impacts on the Moon, sufficiently massive as to transport lunar material to Earth. These repeated episodes strengthen the likelihood that Mars, too, experienced such events and that Earth has sampled the resulting debris.

5. Conclusions

Differences in trace element contents, particularly for siderophile and mobile elements, indicate the unique history of each lunar meteorite-ALHA81005, Y-791197 and -82192/3. Practically every element we determined is highly enriched in Y-791197, probably by lunar volcanic (fumarolic) deposition: in fact, this sample is one of the most trace element-rich lunar samples known.

Other lunar meteorites have lower trace element contents. Gallium, which behaves as a lithophile in these samples, Rb and Cs have similar contents in whole-rock samples of ALHA81005 and Y-82192: the only other lithophile reported here, U, is about $2\times$ lower in the latter. Siderophilic Au is somewhat enriched in Y-82192 relative to ALHA81005, perhaps because it was deposited by ancient meteorite impacts on the Moon. Ten other mobile chalcophile and siderophile trace elements are uniformly enriched in whole rock samples of Y-82192 indicating micrometeorite admixture of $2.4\pm0.8\%$ Cl-equivalent compared with a value of $1.3\pm0.5\%$ Cl-equivalent in ALHA81005. These admixtures occurred when the parent regolith dust was exposed on the surface: in Y-82192, deposition occurred earlier and more rapidly than in ALHA81005. Later shock melting did not fractionate trace elements markedly but did cause slight loss of 9 mobile chalcophile and siderophile elements. About half the trace elements we determined in a clast in Y-82192 are depleted by about $6\times$ relative to whole-rock values; other elements (Ag, Bi, Co, Ga, Sb, Se, Tl) show no such trend.

These and other differences in the properties of the 3 lunar meteorites indicate small but real parent regolith differences: each was probably launched Earthward by a separate massive impact on the Moon. Hence, impacts on the Moon during the past 10^5–10^6 years, the terrestrial age range for most Antarctic meteorites, large enough to allow debris to acquire a shock-induced impulse sufficient to overcome lunar gravity, *i.e.* $\geq$2.4 km/s, are not uncommon: they may not have been rare on Mars either.

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